Elastic and Viscous Stiffness of the Canine Left Ventricle

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Apparatus:

- ➜ Mongrel dogs on a heart-lung machine
- ➜ A balloon on the end of a fluid-filled cannula, filled with saline, is inserted into the left ventricle
- ➜ Inflow and outflow tracts of the ventricle occluded with teflon buttons
- ➜ A piston attached on the external end of cannula

Some Figures:

- ➜ Piston is driven at 22 Hz to produce volumetric perturbations
  - Electrical equivalent of a forcing function
- ➜ Heart is paced at a consistent 2 Hz

Linearity: The concept of linearity dictates additivity and homogeneity. The following equations sums these two. For an input x(t), and an output y(t):

$$A\,x_1(t) + B\,x_2(t) \longrightarrow A\,y_1(t) + B\,y_2(t)$$

Author's Assumption of Linearity:

➜ Cardiovascular system limits the verification capabilities

➜ Verify the assumption backwards

- Look for input frequencies to show up at the output
- Frequency domain analysis: gain versus frequencies

Volumetric Perturbation $V_0 cos(\omega t)$:

$$P(t) = P_0 cos(\omega t + \Psi) \tag{1}$$

$$\frac{1}{K}\ddot{P}(t) + \frac{1}{\eta}\dot{P}(t) + \frac{1}{m}P(t) = \frac{1}{\alpha}\ddot{V}(t) \tag{2}$$

Taking Laplace Transform:

$$H(s) = \frac{V(s)}{P(s)} = \frac{\frac{s^2}{K} + \frac{s}{\eta} + \frac{1}{m}}{\frac{s^2}{\alpha}} \tag{3}$$

Stiffness:

- Viscous: $n\omega = \frac{\alpha P_0}{V_0 sin(\Psi)}$
- Elastic: $K = \frac{\alpha P_0}{V_0 cos(\Psi)}$
- Total: $= \frac{1}{\sqrt{(1/K)^2 + (1/(\eta\omega))^2}} = \frac{\alpha P_0}{V_0}$

A MATLAB Simulation:

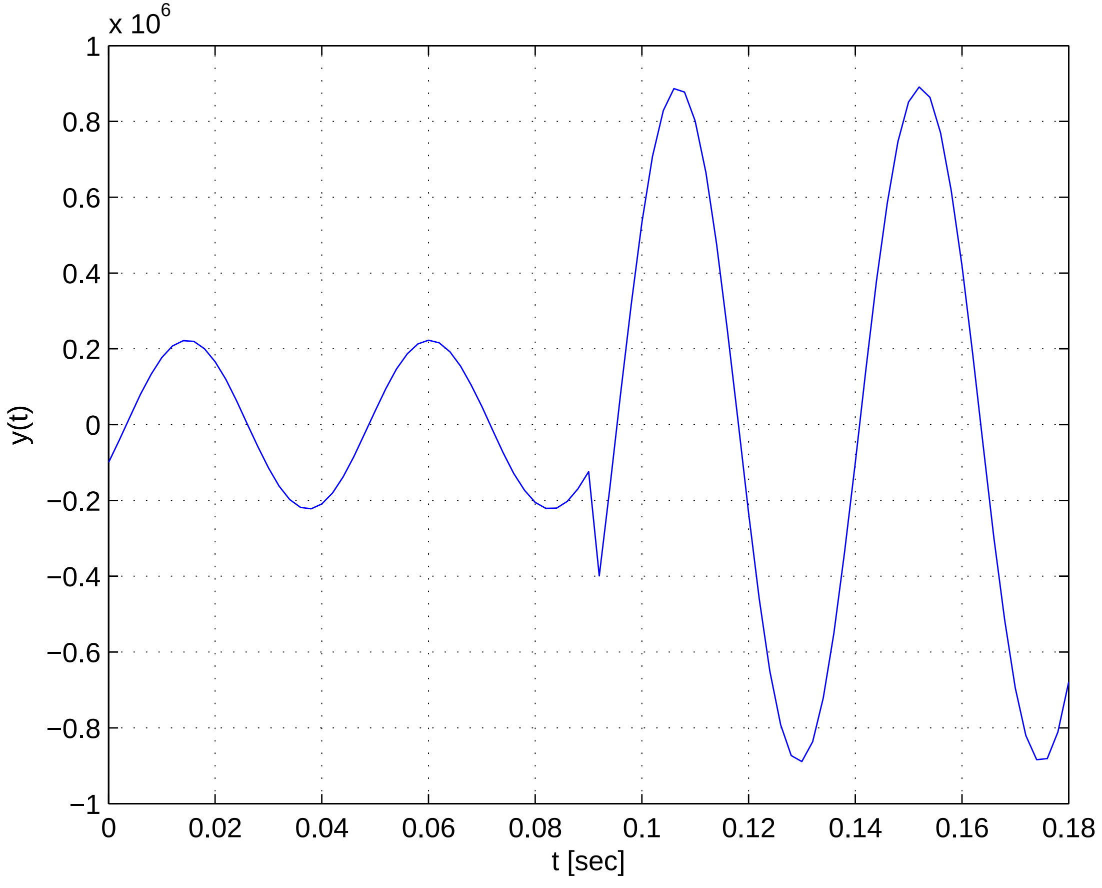

Figure 1: System: Diastole and Systole

Author's Findings:

- Ventricular Pressure $\uparrow \Rightarrow$ Total Stiffness $\uparrow$
- Total stiffness increases as the cardiac cycle advances from diastole to systole
- Elastic stiffness dominates this increase
- Different dogs had different stiffness curves

Questions Projected in 1974:

- Reversal of the indirect relationship between SR and pressure at the peak of systole?
- Whether stiffness is directly related to the contractile state of myocardium (or E_{max})?

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  % Vd and Vs: Viscous Stiffness in diastole and systole
Vd = 0.4e6; Vs = 4*Vd;
alpha = 77;
m = 50;

% Viscous Damping: eta
etad = 1/Vd; etas = 1/Vs;

Kd = 0.4e6; Ks = 10*Kd;

% Transfer Functions
Hd = tf([1/Kd, 1/etad, 1/m], [1/alpha 0 0]);
Hs = tf([1/Ks, 1/etas, 1/m], [1/alpha 0 0]);

w = 2*pi*22;
Fs = 500; T = inv(Fs);
t = 0:T:0.09;
H = evalfr(Hd, j*w);
y1 = abs(H)*cos(2*pi*22*t + angle(H)*180/pi);

H = evalfr(Hs, j*w);
y2 = abs(H)*cos(2*pi*22*t + angle(H)*180/pi);

t = 0:T:2*0.09;

y = [y1 y2]; y = y(1:end-1);
plot(t, y), grid, xlabel('t [sec]'), ylabel('y(t)');
```